

QUALITY ASSURANCE FOR DEEP FOUNDATION ELEMENTS

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Abstract

Cross-hole sonic logging (CSL) has become a universal standard, non-destructive testing (NDT) method for evaluating the integrity of foundation structures for maintaining quality assurance and quality control (QA/QC) of transportation facilities and infrastructures. CSL Tomo 3D™ is a three-dimensional cross-hole sonic logging (CSL) data processing technology that enhances the capabilities of techniques currently used to characterize the interior structure of deep foundation elements and simplifies presentation of the processed data as compared to other methods. The true three-dimensional representation offered by CSL Tomo 3D™ provides greater detail of the interior structure making defects easier to classify.

This paper will present an overview of CSL Tomo 3D™ and its application for quality assurance/quality control of deep foundation elements.

About Seismic Tomography

Seismic tomography is based on the principle that acoustic waves propagate at different velocities through different types of material or the same material with different physical properties. That is, seismic waves travel faster in strong, competent material and slower in weaker materials (e.g., voids, broken or weathered zones, unconsolidated material) (Westman, et al., 1996; Nur, 1987; Shea-Albin, et al., 1991). Velocity tomographic images represent the velocity as measured between seismic sources and receivers.

To determine the seismic velocities within an imaged area, the time required for seismic energy to travel from known source and receiver locations is measured. The velocity is then computed by dividing the distance traveled from source to receiver by this travel time. In material with a homogenous velocity distribution, this distance is simply a straight-line distance, or straight ray path, from the source to the receiver. However, in material with velocity variations, this distance may significantly increase due to curvature of the ray path through higher velocity material between the source and receiver. With appropriate source and receiver geometry, it is possible to iteratively construct an accurate velocity model of the area surveyed.

There are numerous factors that may cause variations in velocity. Different material types usually have different material/seismic properties, but variations within the same material type are also commonly encountered. Variations in stress, fracture extent, water saturation, material homogeneity, etc., all may have a significant effect on velocity. In areas where features such as fracture zones or cavities exist, the seismic waves may travel at a lower velocity, or may travel across an increased distance to pass around the anomaly.

About CSL Tomo 3D™

CSL Tomo 3D is a three-dimensional cross-hole sonic logging (CSL) data processing technology that enhances the capabilities of techniques currently used to characterize the interior structure of deep foundation elements and simplifies presentation of the processed data as compared to other methods. CSL Tomo 3D™ is designed to provide multiple iterative reconstructions of calculated travel times (ray paths) determined from the raw seismic data collected from field measurements of the seismic ground velocity. The velocity tomography generates a reconstructed material velocity image from signal travel-time data. The ray path and velocity models are constructed to estimate travel time and the refraction path for each ray. This is accomplished by approximating the velocity medium as a continuous grid mesh

with assigned node values. The ray paths are calculated by propagating a finite-difference wave front across the surveyed zone from a known source location. For low-velocity contrasts, straight rays are often assumed. In higher velocity contrasts, rays will bend (refract), resulting in longer ray paths. Differences between the estimated and measured travel times are used to iteratively update the tomograms in regions along each ray path. Refraction paths are also adjusted to account for changes in the velocity mesh. Iterations are repeated until the velocity mesh converges to a solution. The true three-dimensional representation offered by CSL Tomo 3D™ provides greater detail of the interior structure, making defects easier to classify.

Case Study 1

The Piney Creek Bridge Replacement project was designed by the Federal Highway Administration (FHWA). The bridge is two spans with four drilled shafts in each abutment and four drilled shafts in the pier. The 912-mm-diameter abutment drilled shafts and the 1,220-mm-diameter pier drilled shafts were designed for skin friction only and extended to an estimated depth of about 11 m. Each shaft was drilled into rock sockets with permanent corrugated steel casing extending to the pile top. Larger diameter casings extend to the top of bedrock, and the annulus between the two casings was filled with sand. The 912-mm and 1,220-mm shafts were equipped with three and four CSL access tubes, respectively.

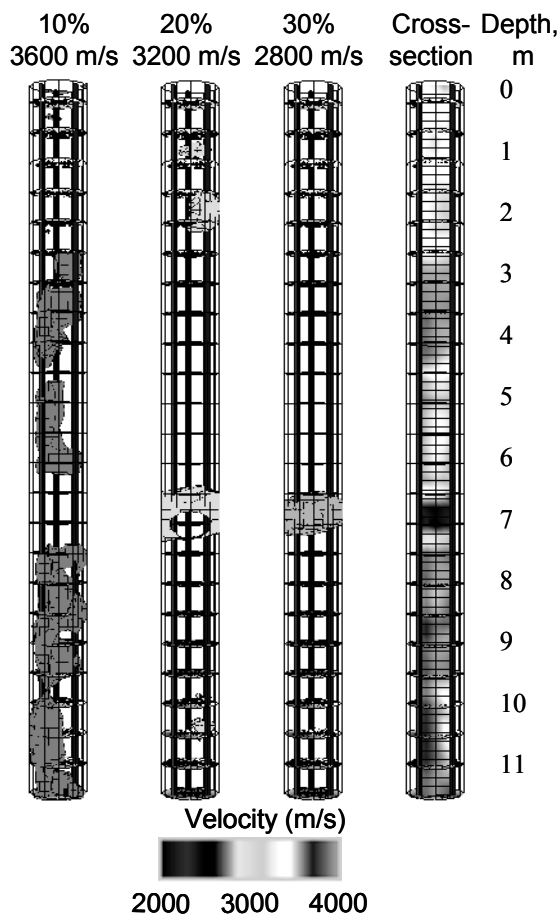
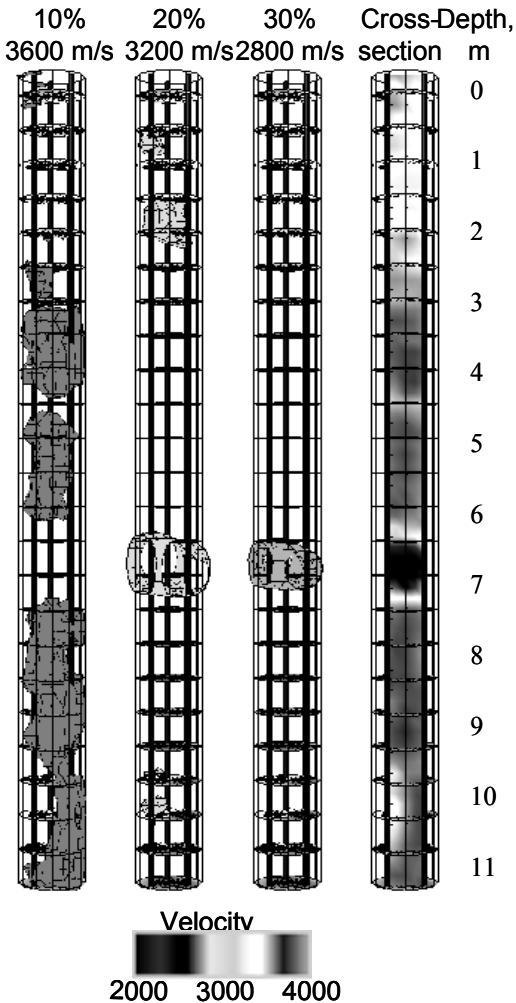


Figure 1. Cross-section Tubes 1 & 2 – Abutment 2, Shaft 4 (A2-4).

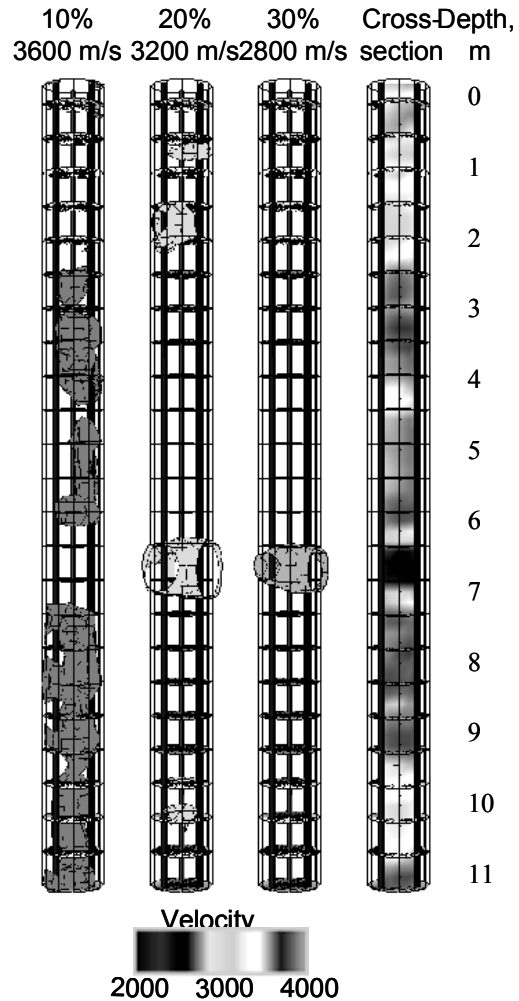
The CSL logs from abutment 2 shaft 4 (A2-4) indicated a significant signal delay between all tubes at a depth of approximately 6 to 7 m from the top of the shaft. A signal velocity delay of about 14%, 29%, and 50% was recorded between access tubes 1-2, 1-3, and 2-3, respectively. Based on these CSL test results, it was determined that a significant zone of deficient concrete existed in A2-4, and a remediation strategy was required. The standard procedure to assess the problem would be to obtain core samples from the anomalous zone to physically inspect the concrete, to confirm the actual location, and to grout encountered deficient zones. Since the CSL logs did not indicate the size, geometry, and severity of the defect, a three-dimensional velocity tomographic analysis of the A2-4 shaft using the CSL data was used to produce an image of the geometry and location of the anomaly. The objective of this investigation was to accurately define the geometry and location of the anomalous area, propose a plan for corrective action, and determine the effectiveness of the recommended plan.

In reviewing the CSL data, the average ultrasonic apparent velocity was calculated to be approximately 3,660 m/s. The three-dimensional images indicated most of the area within the shaft had a velocity greater than the average that indicates sound concrete. The zones with velocity contours of 10% (velocity of 3,294 m/s in green) and 20% (velocity of 2,928 m/s in blue) reduction were plotted. A minor zone of about 10% reduction was depicted in the upper part of the shaft between 0.5 m and 2.5 m,

and a 20% reduction zone that extended across the entire shaft diameter was depicted between 6.6 m and 7.5 m depth. After reviewing the tomographic images (Figures 1 through 3), the defects were located



*Figure 2. Cross-Section Tubes 2 & 3
– Abutment 2, Shaft 4 (A2-4).*



*Figure 3. Cross-Section Tubes 3 & 1 –
Abutment 2, Shaft 4 (A2-4)*

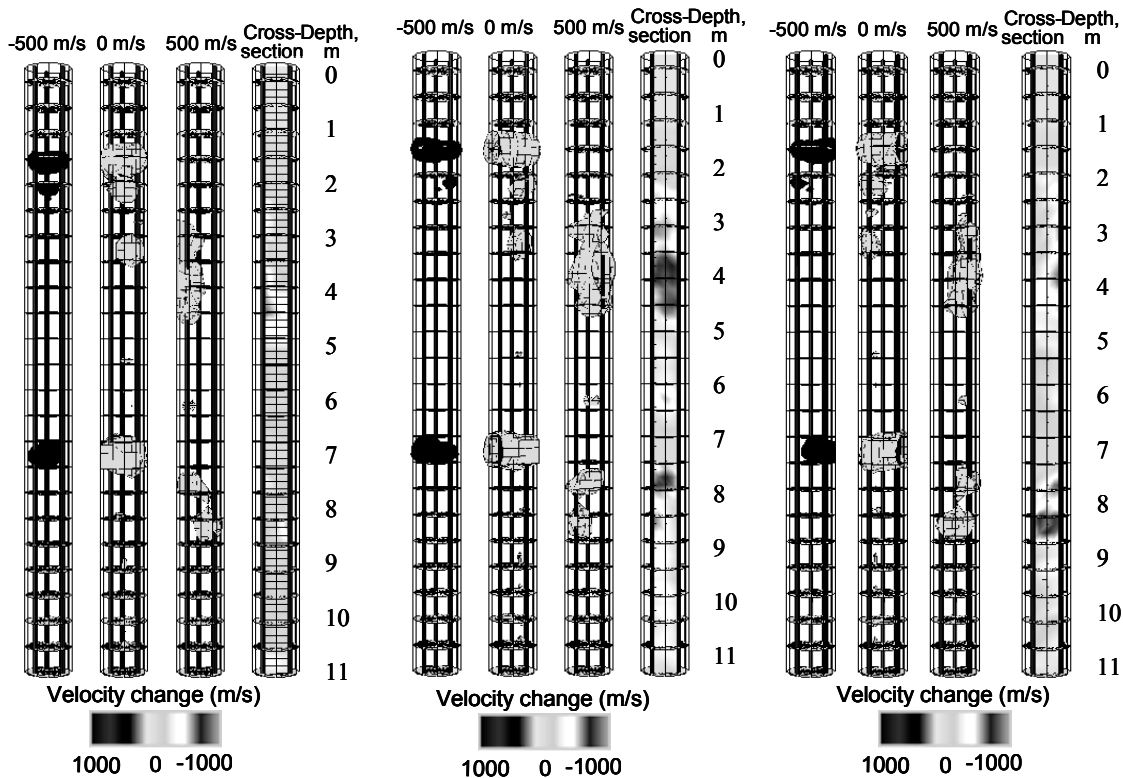
within shaft A2-4. The contractor drilled two core holes and retrieved concrete core samples for physical investigation and evaluation.

Core inspection indicated that no defective concrete was encountered during the coring in the SE core hole (tubes 2-3). However, the SW coring (tube 2-3) encountered a weak zone 0.15 m long between 6.5 m and 6.65 m below the top of the shaft. The anomaly consisted of a pocket of clean, well-graded, yellow-brown sand in one-half of the core. The sand pocket abruptly terminated in good concrete.

Further analysis of the CSL data with the three-dimensional tomography techniques was conducted to determine the percent in the velocity deviation that should have been contoured to match the core results. The data were reprocessed, and it was determined that the sand pocket coincided with the 30% velocity reduction and not the 20% as specified in the guidelines.

A pile repair procedure was developed with the objective to improve the defect zone in the A2-4 drilled shaft. Permeation grouting to improve the strength and reduce the permeability of the low-density zones within the shaft was recommended. After the successful grouting of the A2-4 shaft, CSL retesting was performed using the standard procedures. The CSL retest results indicated a minor signal velocity reduction at a depth of approximately 6 m from the top. The velocity reduction ranged from 7% for the tube pair 1-2 to about 16% for tube pairs 1-3 and 2-3. The average velocity was estimated at 3,800 m/s

for pairs 1-2 and 2-3, and 3,900 m/s for pair 1-3. The results indicate that the grouting procedure had improved the concrete density within the anomalous zone and reduced the intensity of the defect, but did not completely eliminate the defect. Based on the retest results and the location of the defect within the drilled shaft, the drilled shaft was acceptable for further bridge construction. Difference tomograms between the signals obtained from the pre-grouting and post-grouting tests were calculated and are presented in Figure 4 through 6 as tomograms representing cross-sections between access tube pairs. These tomograms show areas of velocity improvement in three-dimensional contours.



Case Study 2

NSA was contracted to process CSL data collected from the shaft of a bridge foundation project. NSA applied its CSL Tomo 3D™ seismic tomographic imaging software to convert the data to two-dimensional and three-dimensional colored seismic velocity images of the shaft to provide information on the quality of the shaft construction. With respect to the CSL data used to generate the seismic velocity images for this project, NSA was provided only the first arrival times for each data file and did not have access to the raw waveform data. Therefore, NSA cannot address the quality of the data or the accuracy of the first arrival “picks.” Also, please note the lack of coverage around hole 4 near the top of the column, which is a consequence of losing acoustic coupling in the hole due to the water level dropping in the hole prior to and during data collection. The lack of ray path coverage for the top 5 feet of hole 4 reduces the reliability of the image for that zone, and the low-velocity anomaly shown in that region may be an artifact resulting from the lack of data.

Figures 7 and 8 show the perimeter panels defined by holes 4-1-2 and 4-3-2, respectively. Figures 9 and 10 show the diagonal panels defined by holes 4-2 and 1-3, respectively. In these four figures, three zones are shown that have velocities lower than 2,600 m/sec (purple zones). Of these three zones, the one within the top 5 ft of the column must be discounted due to the lack of data from hole 4, and the zone between 4 ft and 8 ft only affects the perimeter of the column.

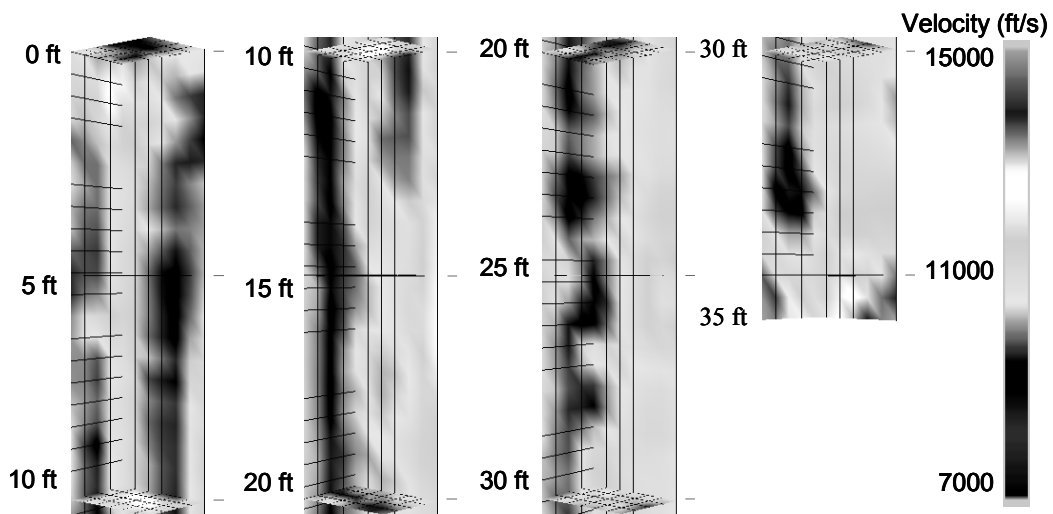


Figure 7. Holes: 4-1-2, 0 ft to 35+ ft.

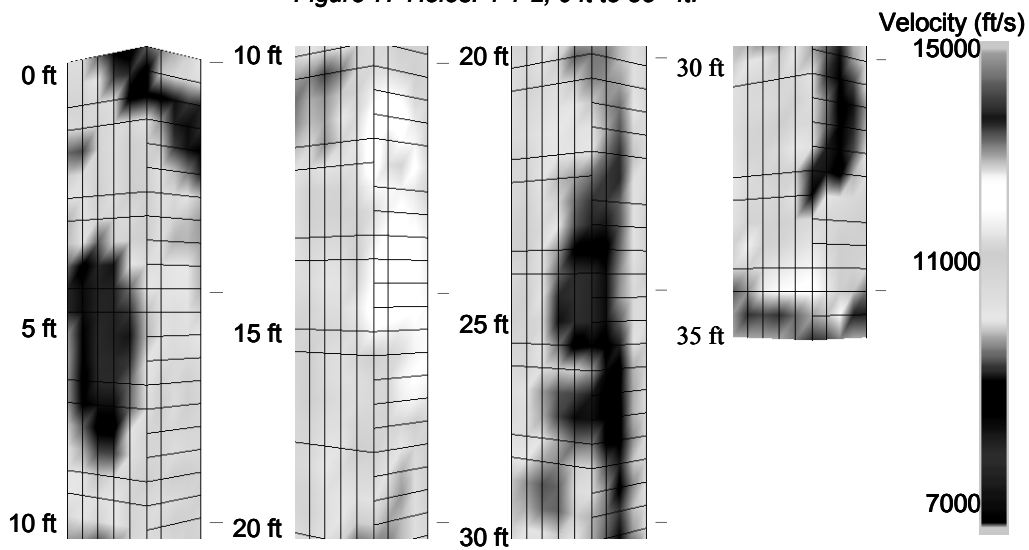


Figure 8. Holes: 4-3-2, 0 ft to 35+ ft.

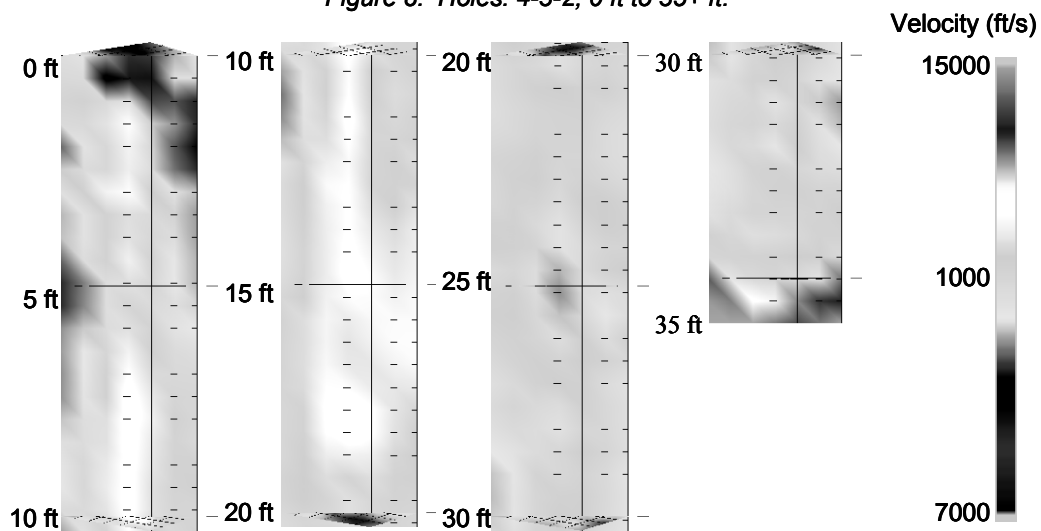


Figure 9. Panel 4-2, 0 ft to 35+ ft.

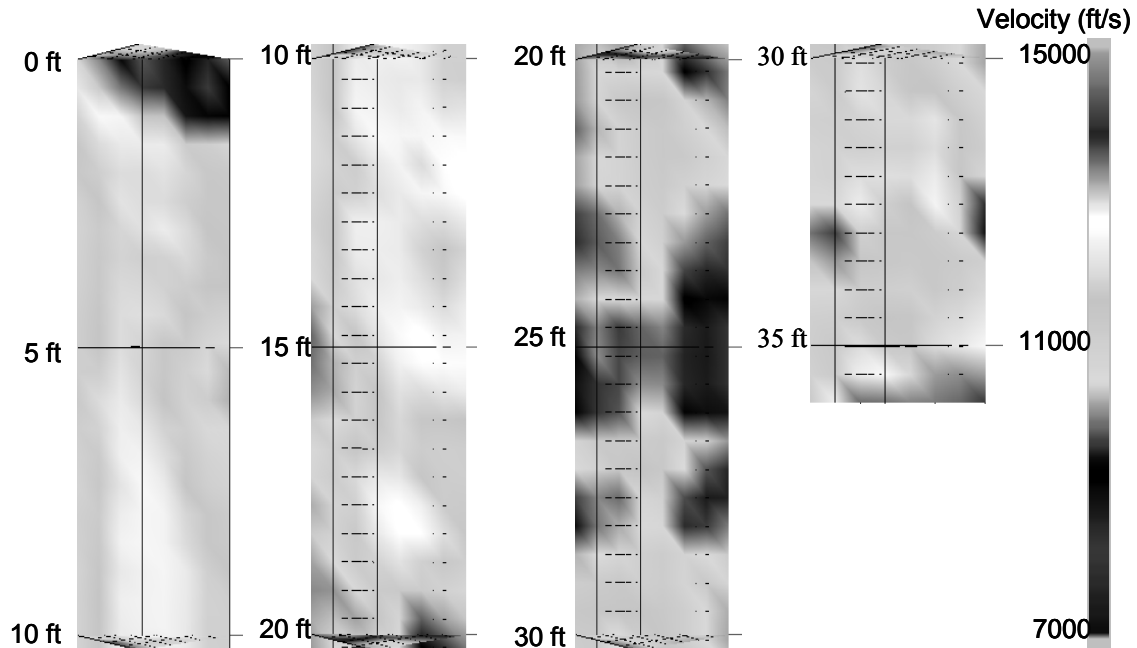


Figure 10. Panel 1-3, 0 ft to 35+ ft.

Images were generated showing three-dimensional views down the column at 5-ft intervals. Figures 11 and 12 are views down the column showing velocity contours for 2,450 m/s, indicating concrete that is possibly inferior in quality. The four boreholes define the perimeter panels shown, and a horizontal plane is shown at the bottom of the 5-ft interval.

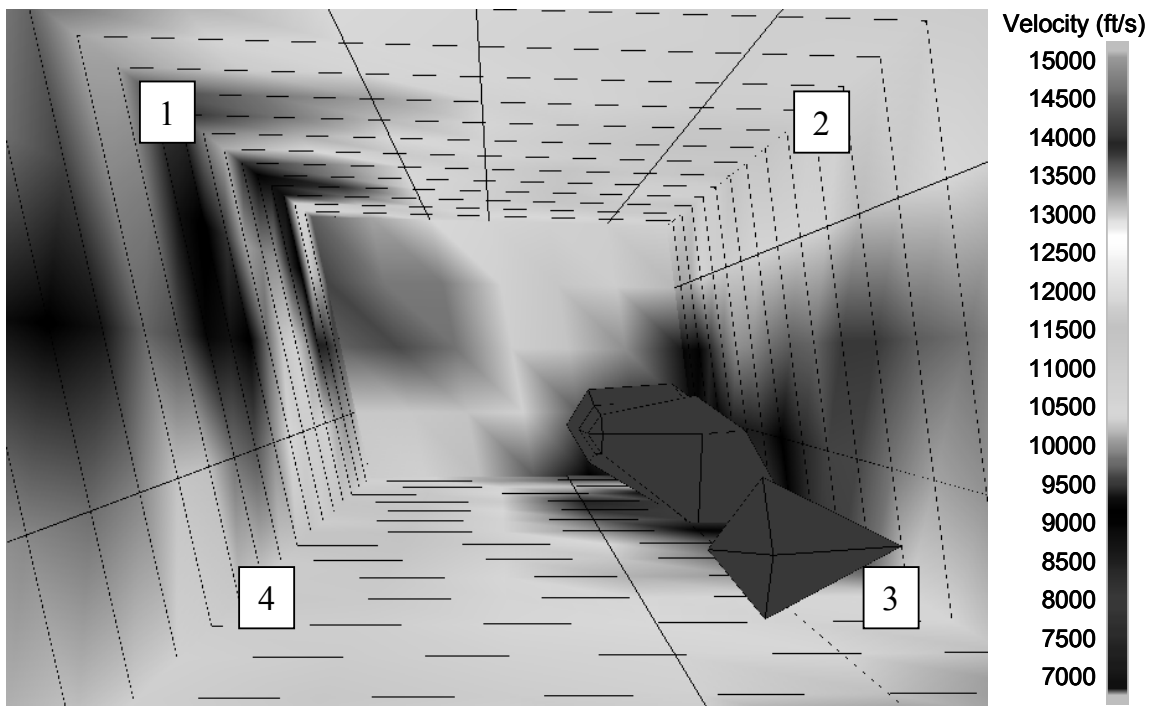


Figure 11. Depth: 22.5-27.5 ft, Contour 8,000 ft/s.

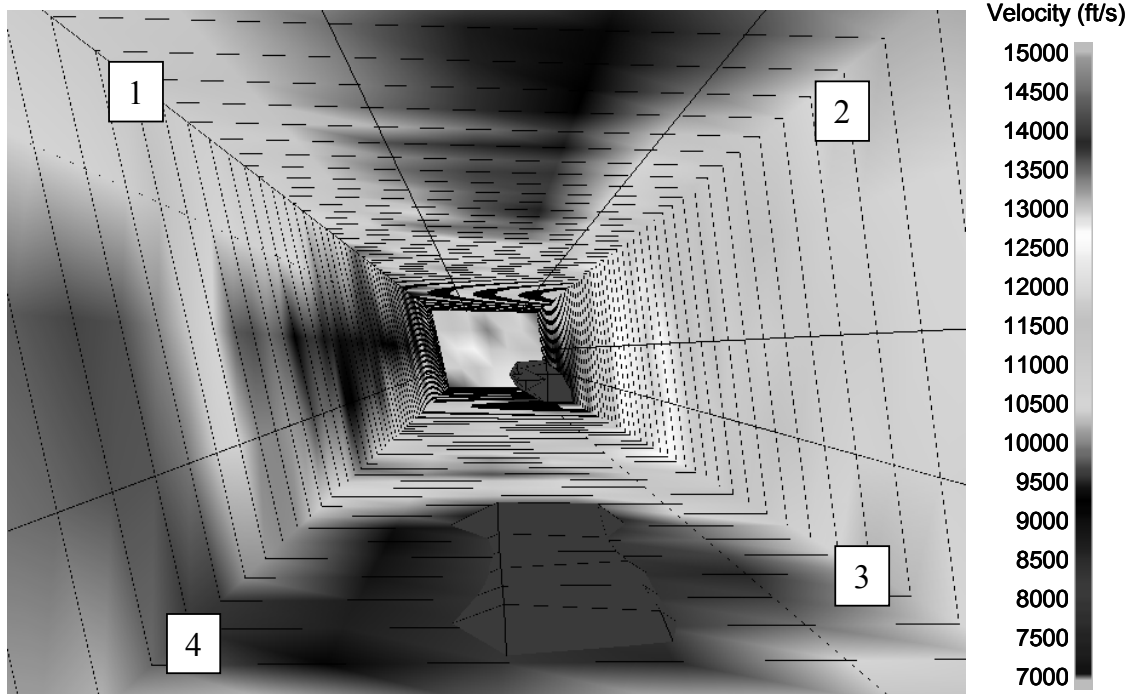


Figure 12. Depth: 5-35 ft, Contour 8,000 ft/s.

For all images included in this report, the velocities shown may not be absolute velocities, but they are accurate relative velocities. Green areas are near the average seismic velocity for the column, yellow and red areas have proportionally higher velocities, and the blue and purple areas have proportionally lower velocities and could indicate problematic zones. Any inaccuracy of the absolute velocities is due to the first arrival “picking” methodology. Most “picking” programs tend to “pick” first arrivals slightly later in time than the actual first arrival time. When the distance between sources and receivers is small, such as with this shaft, any inaccuracy in “picking” the first arrival can contribute to a significant error in the velocity calculations. Most first arrival “picking” programs consistently “pick” the same point in the data relative to the first arrival, so the relative velocities are accurate. If the absolute velocity can be determined for several specific locations in the shaft by laboratory test, these test results can be used to calibrate all the velocities of the tomogram.

It must also be noted that the actual minimal velocity of a small low-velocity zone may not be accurately indicated in the tomographic image. If the seismic energy that travels around a low-velocity zone reaches the receiver before the energy traveling through the low-velocity zone, the actual velocity of the zone may be less than that indicated. For example, if a spherical void existed in a shaft, the seismic energy that travels around the perimeter will travel up to 57% further to reach the receiver on the other side than energy traveling through the diameter of the sphere; therefore, the maximum decreases in velocity that the tomogram would indicate for the void is 1/1.57 or 64% of the velocity of the zone around the void.

Conclusions

The traditional non-destructive methods of assessing the integrity of deep foundation elements have fallen short of providing true three-dimensional representation of the subsurface site conditions. Results of CSL testing are typically displayed with two-dimensional representations. When a defect or anomaly is detected, the only information available is the elevation within the shaft where this feature exists. By using CSL Tomo 3D™ seismic tomography to reprocess the CSL data, the size, shape, and orientation of the defect can be determined. With this information the engineer is better able to determine if the shaft must be replaced or whether repair is an option. Eliminating inferior shafts increases the reliability and

safety of the overall structure. If a shaft can be repaired, detailed knowledge of the feature allows the engineer to prescribe the most cost-effective methods for repairing the shaft. Further, applying difference tomography between the original CSL data and the post-repair CSL data allows the engineer to ascertain the effectiveness of the repair, increasing the level of confidence that the shaft will meet the design requirements. CSL Tomo 3D™ seismic tomography has evolved into a powerful geotechnical tool for cost-effective quality assurance assessment of various constructed support systems.

The case studies for deep foundation integrity assessment presented here are but a few applications of the many projects where three-dimensional seismic tomography has been applied to highways, bridge piers, retaining wall foundations, sinkholes, old mine workings, slope excavation, and sewer and tunnel site characterization. To date, the use of the three-dimensional tomography technology in providing volumetric images has allowed the design engineers and contractors to better understand the complex geologic environment of the site, and the risks and expenses associated with “changed conditions” can be greatly reduced.

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